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DFA & GRA BASED MULTI OBJECTIVE OPTIMIZATION DURING HOT MACHINING OF AISI D3 TOOL STEEL USING TNMG INSERT

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ABSTRACT

In this paper, an experimental investigation is carried out to optimize performance characteristics (surface roughness and material removal rate) simultaneously in hot machining operation using Grey relational analysis (GRA) and desirability function analysis (DFA). The experiments are conducted on CNC lathe with AISI D3 tool steel as work material and PVD coated TNMG-HM tool is inserted as a tool material which is based on Taguchi L18 orthogonal array design. The work-piece is heated using butane torch flame which is cost effective method compared to other heating techniques used in hot machining process. The influence of spindle speed, feed and depth of the cut were analyzed on the performance of surface roughness and material removal rate. The optimal turning parameters are determined by composite desirability index and grey relational grade. Analysis of variance (ANOVA) is used to determine the influence of parameters which significantly affect the responses simultaneously. From the study, it is concluded that the machining performance is significantly improved.

KEYWORDS: AISI D3 Tool Steel, PVD Coated TNMG-HM Tool Insert, Surface Roughness, Material Removal Rate, Grey Relational Analysis, Desirability Function Analysis, ANOVA & CNC Lathe

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Original Article

INTRODUCTION

The basic of hot machining operation is to first soften the work-piece by preheating and thereby shear strength gets reduced in the vicinity of the shear zone. The use of hot machining has become very useful in the machining of high strength temperature-resistant (HSTR) alloys. Hot machining has two functions to perform, one, to machine some HSTR alloys which are unmachinable in the conventional machining method. Second, to improve tool life and this eventually improves the production rate. Increase in productivity and the quality of the machined parts are the main challenges of the metal based industry. Surface finish and material removal rate are the two important parameters needed to be considered in manufacturing industry to ensure the aesthetic appeal to the product as well as improved productivity. In order to obtain better surface finish and increased material removal rate, proper setting of cutting parameters is crucial before the process takes place. Factors such as spindle speed, feed rate, depth of cut that control the cutting operation can be set up in advance. In the present work, AISI D3 tool steel was selected as a work material which finds applications in the manufacture of blanking & forming dies, press tools, punches, bushes, forming rolls and many more. For the purpose of experimentation, factorial design experiments are considered as per Taguchi DOE. By advocating Taguchi design, a clear understanding of the nature of variation and economical consequences of quality engineering in the world of manufacturing can be clearly got through. In the present study, Desirability function analysis and Grey relational analysis were performed to combine the multiple performance characteristics into one numerical score which is an indicative of the optimal process parameter setting. Analysis of

variance (ANOVA) is also performed to investigate the most influencing parameters on the surface roughness and material removal rate.

W. H. Yang & Y. S Tang [1] envisages that the Taguchi method is a powerful tool to design optimization for quality and is used to find the optimal cutting parameters for turning operations. An orthogonal array, the signal to noise ratios and ANOVA are employed to investigate the cutting characteristics of S45C steel bars using Tungsten carbide cutting tools. Through this study, not only optimal cutting parameters for turning operations obtained, but also the main cutting parameters that affect the cutting performance in turning operations are found. M. P. Jenarthanan & R. Jeyapaul [2] presents a new approach for optimizing machining parameters on milling glass-fibre reinforced plastic (GFRP) composites. Optimization of parameters was done by an analysis called desirability function analysis (DFA) which is a useful tool for optimizing multi response problems. P. S. Kao & H. Hocheng [3] explains the usefulness of Grey relational analysis for multi-input, discrete data and experimental study and also developed an application of grey relational analysis for optimizing the electro polishing of 316L stainless steel with multiple performance characteristics. R. K. Suresh et al. [4] dealt with an experimental investigation carried out for machinability study of hardened AISI D3 tool steel in combination with CVD coated inserts of different styles using vegetable oils as cutting fluid under minimum quantity lubrication and to obtain optimum process parameters using novel MCDM method viz., Deng's method and WASPAS method. Sheik Rehaman et al. [5] performed a series of machining experiments on Inconel 718 has been carried out as per Taguchi L18 orthogonal array using coated and uncoated carbides to establish the influence of surface temperature, spindle speed, feed and depth of cut on forces (feed, radial and thrust forces), surface roughness, MRR, power consumption and hardness in hot-turning of Inconel 718 alloy. Gajjanna et al. [6] presented the optimization of machining parameters in hot machining using Taguchi Method. Experiments were conducted on 15–5 PH stainless steel using coated carbide tool based on Taguchi L9 orthogonal array design. The work piece material was heated using oxy-acetylene gas flame. The effect of speed, feed and depth of cut on surface roughness, tool wear and metal removal rate was found and the optimum conditions were determined. R. K. Suresh et al. [7] focused on an approach based on Grey relational analysis and Desirability function analysis for optimizing the process parameters during turning of AISI 8620 alloy steel with CVD coated tool with multiple performance characteristics. Venkatesh Ganta and D Chakradhar [8] focused on optimizing the cutting conditions for the average surface roughness (Ra) and metal removal rate (MRR) obtained in hot machining of 15–5PH martensitic stainless steel with 40 HRC. Hot machining experiments were performed on a lathe machine using K313 carbide tool insert. Experiments were conducted based on Taguchi L18 orthogonal array. The results of the study indicate that the feed rate has the most significant effect on surface roughness. Cutting speed and feed rate has the most significant effect on material removal rate. Ketul M. Trivedi et al. [9] carried-out experimental investigation that had been carried out for hot machining of AISI 4340 steel using a tungsten carbide cutting tool. The influence of the cutting parameters namely cutting speed (Vs), feed rate (fs) and depth of cut (ap) at 200°C, 400°C and 600°C hot machining of AISI 4340 steel on surface roughness are studied.

From the above, it is evident that a little work has been reported on AISI D3 tool steel work with combination of PVD coated tool during hot machining. Also little work has been reported on Desirability function Analysis and Grey relational analysis simultaneously on hot machining operations. Hence the experimentation is done on above said combination of work piece and tool and optimization method and the Desirability function analysis and Grey relational analysis are put forth.

EXPERIMENTATION

In the present study, four process parameters were selected with mixed design shown in Table.1. The experimentation was carried out using L18 orthogonal array based on Taguchi design of experiments. The work material selected for this experiment is AISI D3 tool steel of 40 mm diameter, length 100 mm. The chemical composition of AISI D3 tool steel is given in Table.2

Table 1

Process parameters	Symbol	Level-1	Level-2	Level-3
Machining Environment	ME	Dry	Heated condition (300°C)	-----
Spindle speed (rpm)	N	200	250	300
Feed rate (mm/rev)	F	0.05	0.07	0.07
Depth of cut (mm)	d	0.50	1.0	1.5

Table 2

Table1Element	Carbon	Silicon	Mn	Ni	Cr	Mo	S	P	Al	B
% composition	2.179	0.511	0.511	0.05	12.634	0.178	0.021	0.025	0.178	0.065

The turning tests were carried out on CNC lathe machine–supper jobber 500 model lathe (Figure 1) to determine the response characteristics for various runs of experiment. Surface roughness is measured using "SVC 4500" surface roughness measuring instrument. The material removal rate (mm^3/min) is calculated using formula:

$$MRR = [\pi/4(D_1^2-D_2^2)L]/t \ mm^3/min$$

Where, D_1 = Diameter of the work piece before turning, mm

D2 = Diameter of the work piece after turning, mm

L = Length of turning, mm

t = Machining time, min

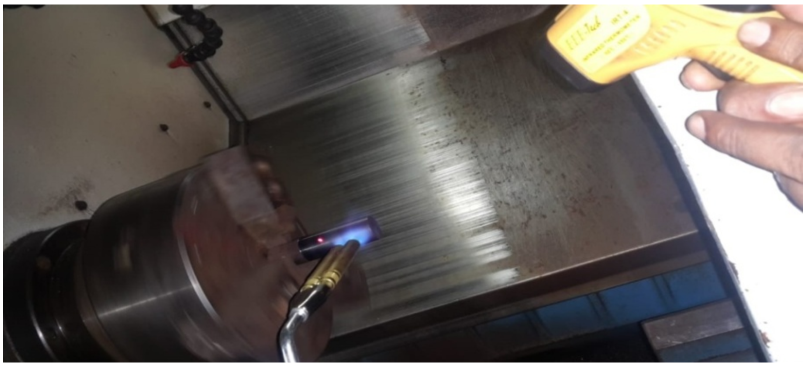

Figure 1: Experimental Set-Up (Hot Machining).

METHODS USED

Desirability Function Analysis

Desirability function analysis is widely accepted method used in manufacturing industry. Desirability function analysis is used to convert multi response characteristics into single response characteristic. Derringer and suich [10] popularized the concept of DFA as a simultaneous optimization technique which is proved to be useful in

solving multi response optimization problems. In view of this, complicated multi response characteristics can be converted into single response characteristic which is termed as composite desirability. In the present study, multi responses such as surface roughness and material removal rate are combined as composite desirability using desirability function analysis.

The steps involved in the optimization process are detailed as follows:

Step 1: The first step is to calculate desirability index (di) for each of the process parameters, i.e., surface roughness and material removal rate. The desirability index values are tabulated. It is calculated based on the desirability function shown in the Equations (1) and (2), respectively for the cases smaller is better and larger is better. In this study, surface roughness need to be minimized and material removal rate need to be maximized.

Step 2: The second step is to evaluate the composite desirability based on equation (3).

Step 3: The third step is to determine optimality condition based on highest composite desirability index. Also the ranking of process parameters is estimated.

Step 4: The next step is to perform ANOVA by which contribution made by each parameter influencing the combined objective is estimated.

Step 5: The last stage is to calculate the values from conformity test based on optimum level of parameters is found out.

For smaller is better,

$$d_i = \frac{yi-ymax}{ymin-ymax} \tag{1}$$

For larger is better,

$$d_i = \frac{yi-ymin}{ymax-ymin} \tag{2}$$

where, d_i is desirability index for a particular level

y_i is i^{th} normalized value

y_{min} is minimum of particular column values(response characteristic)

y_{max} is maximum of particular column values(response characteristic)

$$dc = \sqrt[w]{d1^{w1}} d2^{w2} d3^{w3} \ldots \ldots . . dn^{wn} \tag{3}$$

Where w_1 and w_2 are the weights assigned. Since both surface roughness and material removal rate play a significant role in improving productivity and quality of the product during machining operation, more weightages are assigned to surface roughness and material removal rate. The weights assigned for surface roughness, w_1=0.5, for MRR, w_2=0.5.

GREY RELATIONAL ANALYSIS

In the procedure of GRA, the experimental result of surface roughness, material removal rate, interface temperature and flank wear are normalized at first in the range between zero and one due to the different measurement units. This data pre-processing step is termed as 'grey relational generating'. Based on the normalized experimental data, grey relational

coefficient is calculated to correlate the desired and actual experimental data using equation (4). The overall Grey Relational Grade (GRG) is determined by averaging the grey relational coefficient corresponding to the selected responses using equation (5). This approach converts a multiple response process optimization problem into a single response optimization by calculating overall grey relational grade. The normalized experimental results can be expressed as follows.

For larger is better,

$$xi(k)=\frac{yi(k)-\min yi(k)}{max yi(k)-\min yi(k)}$$

For smaller is better,

$$xi(k)=\frac{\max yi(k)-yi(k)}{\max yi(k)-\min yi(k)}$$

Where $\max yi(k)$ and $\min yi(k)$ are the largest and smallest values of $yi(k)$ respectively.

The Grey relational coefficient $\xi(k)$ for $yi(k)$ is calculated as

$$\xi(k) = \frac{\Delta min+\psi\Delta max}{\Delta oi(k)+\psi\Delta max} \tag{4}$$

Where, $\Delta\, oi(k)$ is the reference sequence deviation which is equal to mod $(\max yi(k) - yi(k))$

ψ is a distinguishing coefficient which varies from 0 to 1, the value of ψ is set as 0.5 to maintain equal weightage of surface roughness and material removal rate.

$$\text{Grey relational grade, } \gamma_i = \frac{1}{n}\sum_{i=1}^{n}\xi i(k) \tag{5}$$

RESULTS

A series of turning tests were conducted to assess the effect of turning parameters on surface roughness and material removal rate and the results of experimentation are shown in Table 3.

Table 3: Experimental Data and Results for 2 Parameters, Corresponding Ra and MRR for PVD Tool

Sl. No.	Machining Environment	Spindle Speed (rpm)	Feed (mm/rev)	Depth of Cut(mm)	MRR (mm^3/min)	SR (µm)
1	DRY	250	0.05	0.5	233.35	1.11
2	DRY	250	0.07	1	683.4	1.82
3	DRY	250	0.09	1.5	930	1.01
4	DRY	300	0.05	0.5	247.8	1.33
5	DRY	300	0.07	1	770.4	1.08
6	DRY	300	0.09	1.5	1568.4	0.85
7	DRY	350	0.05	1	685.8	0.33
8	DRY	350	0.07	1.5	1408.8	0.64
9	DRY	350	0.09	0.5	551.88	2.02
10	Heated condition	250	0.05	1.5	795.54	0.15
11	Heated condition	250	0.07	0.5	441	0.32
12	Heated condition	250	0.09	1	1192.2	0.33
13	Heated condition	300	0.05	1	1053.6	0.28
14	Heated condition	300	0.07	1.5	1007.4	0.54
15	Heated condition	300	0.09	0.5	768.6	0.24
16	Heated condition	350	0.05	1.5	1149	0.24
17	Heated condition	350	0.07	0.5	718.2	0.36
18	Heated condition	350	0.09	1	1138.8	0.36

Tables 4, 5, 6, 7, 8 and 9 depicts the results related with Desirability function analysis and Grey relational analysis

Table 4: Evaluated Results of Composite Desirability

Expt. No.	Experimental Data		Normalized Values		Weighted Normalized Values		Composite Desirability
	SR	MRR	SR	MRR	SR	MRR	
1	1.11	233.35	0.486631	0	0.697589	0	0
2	1.82	683.4	0.106952	0.337103	0.327035	0.580606	0.189879
3	1.01	930	0.540107	0.521816	0.73492	0.722368	0.530883
4	1.33	247.8	0.368984	0.010824	0.60744	0.104036	0.063196
5	1.08	770.4	0.502674	0.40227	0.708995	0.634247	0.449678
6	0.85	1568.4	0.625668	1	0.790992	1	0.790992
7	0.33	685.8	0.903743	0.338901	0.950654	0.582152	0.553425
8	0.64	1408.8	0.737968	0.880454	0.859051	0.938325	0.806069
9	2.02	551.88	0	0.23859	0	0.488457	0
10	0.15	795.54	1	0.4211	1	0.648922	0.648922
11	0.32	441	0.909091	0.155537	0.953463	0.394382	0.376029
12	0.33	1192.2	0.903743	0.718213	0.950654	0.847474	0.805655
13	0.28	1053.6	0.930481	0.614396	0.964615	0.783834	0.756098
14	0.54	1007.4	0.791444	0.579791	0.889631	0.76144	0.677401
15	0.24	768.6	0.951872	0.400921	0.975639	0.633183	0.617759
16	0.24	1149	0.951872	0.685854	0.975639	0.828163	0.807989
17	0.36	718.2	0.887701	0.36317	0.942179	0.602636	0.567791
18	0.36	1138.8	0.887701	0.678214	0.942179	0.823538	0.77592

Table 5: Response Table for Composite Desirability

Process Parameters	Average Composite Desirability				
	Level 1	Level 2	Level 3	Max-Min	Rank
Machining Environment	0.37601	*0.67039	----------	0.29438	2
Spindle speed	0.42523	0.55919	*0.58519	0.15997	3
Feed	0.47161	0.51114	*0.58687	0.11526	4
Depth of cut	0.27079	0.58844	*0.71038	0.43959	1

*Optimum levels

Table 6: ANOVA Based on Composite Desirability

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Sum of Squares	F-Ratio	Percent Contribution
Machining Environment	1	0.38997	0.38998	16.1217	28.270
Spindle speed	2	0.08843	0.04421	1.8278	6.410
Feed	2	0.04117	0.02058	0.8509	2.984
Depth of cut	2	0.61799	0.30899	12.7741	44.800
`Error	10	0.24189	0.02419		17.536
					100.000

Table 7: Grey Relational Analysis for Surface Roughness and Material Removal Rate

Expt. No.	Experimental data		Normalized values		Grey Relational Coefficient		Grey Relational grade
	SR	MRR	SR	MRR	SR	MRR	
1	1.11	233.35	0.486631	0	0.493404	0.333333	0.413369
2	1.82	683.4	0.106952	0.337103	0.358925	0.429961	0.394443
3	1.01	930	0.540107	0.521816	0.520891	0.511151	0.516021
4	1.33	247.8	0.368984	0.010824	0.44208	0.335756	0.388918
5	1.08	770.4	0.502674	0.40227	0.50134	0.455485	0.478413
6	0.85	1568.4	0.625668	1	0.571865	1	0.785933

7	0.33	685.8	0.903743	0.338901	0.838565	0.430627	0.634596
8	0.64	1408.8	0.737968	0.880454	0.65614	0.807042	0.731591
9	2.02	551.88	0	0.23859	0.333333	0.396382	0.364858
10	0.15	795.54	1	0.4211	1	0.463435	0.731718
11	0.32	441	0.909091	0.155537	0.846154	0.371896	0.609025
12	0.33	1192.2	0.903743	0.718213	0.838565	0.63956	0.739063
13	0.28	1053.6	0.930481	0.614396	0.877934	0.564587	0.72126
14	0.54	1007.4	0.791444	0.579791	0.70566	0.543355	0.624508
15	0.24	768.6	0.951872	0.400921	0.912195	0.454926	0.683561
16	0.24	1149	0.951872	0.685854	0.912195	0.614141	0.763168
17	0.36	718.2	0.887701	0.36317	0.816594	0.439819	0.628207
18	0.36	1138.8	0.887701	0.678214	0.816594	0.608431	0.712513

Table 8: Response Table for Grey Relational Grade

Process Parameters	Average Relational Grade				
	Level 1	Level 2	Level 3	Max-Min	Rank
Machining Environment	0.52312	*0.71233	________	0.18921	1
Spindle speed	0.56727	0.61377	*0.63916	0.07192	3
Feed	0.60884	0.57770	*0.63366	0.05596	4
Depth of cut	0.51466	0.61338	*0.69216	0.17750	2
*Optimum levels					

Table 9: ANOVA based on Grey Relational Grade

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Sum of Squares	F-Ratio	Percent Contribution
Machining Environment	1	0.125815	0.12582	12.09072	35.929
Spindle Speed	2	0.01595	0.00797	0.76623	4.554
Feed	2	0.00944	0.00472	0.45333	2.694
Depth of Cut	2	0.09492	0.04746	4.56073	27.106
`Error	10	0.10406	0.01041		29.717
					100.000

CONFIMRATION TEST

The objective of the confirmation at optimum levels is to validate the conclusions drawn during the analysis phase. Once the optimal level of process parameters is selected, the next step is to verify the improvement in response characteristics using optimum level of parameters. A conformity test is conducted using the following equation:

$$\gamma = \gamma_m + \sum_{i=1}^{n} \gamma i - \gamma m$$

where γ_m is total mean of the required responses.

γ_j is the mean of the required responses at optimum level.

n is the number of process parameters that significantly affects the Multiple performance characteristics.

A clear comparison between the predicted and experimental values are presented in Table 10.

Table 10: Comparison of Predicted and Experimental Results using GRA and DFA

DFA	Optimum Process Parameters		
	Initial Process Parameters	Predicted Values	Experimental Values
Level of parameters setting	ME1-N1-F1-d1	ME2-N3-F3-d3	ME2-N3-F3-d3
Surface roughness (µm)	1.11	0.3767	0.29
MRR (mm^3/min)	233.35	1471.148	1492.53

Composite desirability	------	0.9832	0.9429
GRA			
Level of parameters setting	ME1-N1-F1-d1	ME2-N3-F3-d3	ME2-N3-F3-d3
Surface roughness (µm)	1.11	0.3767	0.29
MRR (mm^3/min)	233.35	1471.148	1492.53
Grey relational grade	0.41337	0.8351	0.8552

CONCLUSIONS

Desirability Function Analysis

- The optimal parameters setting with Desirability function analysis lies at a heated condition (Machining environment), 350 rpm (Spindle speed), 0.09 mm/rev (feed) and 1.5 mm (depth of cut). The optimum predicted value for surface roughness is 0.3767 µm, MRR 1471.148 mm^3/min, and composite desirability is 0.9832. Also the experimental value for surface roughness is 0.29 µm, MRR is 1492.53 mm^3/min and composite desirability is 0.9429.
- In case of Desirability function analysis, it is found that both predicted and experimental response characteristics are better as compared to initial machining parameters. To be specific, predicted surface roughness (0.3797µm) and experimental surface roughness (0.29µm) are considerably less as compared to surface roughness at initial setting level which is highly desirable. Also predicted MRR (1471.148 mm^3/min) and experimental MRR(1492.53 mm^3/min) are much higher as compared to MRR at initial setting level which paves the way towards higher production rate. It may be noted that there is a good agreement between the predicted composite desirability (0.9832) and experimental composite desirability (0.9429) and therefore, the condition **ME2-N3-F3-d3** of the process parameters combination was tested as optimal. This encourages in applying the desirability function analysis for optimizing multi response problems.
- Further, Analysis of variance (ANOVA) depicts that depth of cut signifies the most followed by the machining environment affecting multi response characteristics with depth of cut 44.80%, machining environment 28.27% , spindle speed 6.14% and feed 2.98, respectively.

Grey Relational Analysis

- The optimal parameters setting with Grey relational analysis lies at heated condition (Machining environment), 350 rpm (Spindle speed), 0.09 mm/rev (feed) and 1.5 mm (depth of cut). The optimum predicted value for surface roughness is 0.3767 µm, MRR 1471.148 mm^3/min, and grey relational grade is 0.8351. Also the experimental value for surface roughness is 0.29 µm, MRR is 1492.53 mm^3/min and composite desirability is 0.8552.
- In case of Grey relational analysis, it is found that both predicted and experimental response characteristics are better as compared to initial machining parameters. To be specific, predicted surface roughness (0.3797µm) and experimental surface roughness (0.29µm) are considerably less as compared to surface roughness at initial setting level which is highly desirable. Also predicted MRR (1471.148 mm^3/min) and experimental MRR(1492.53 mm^3/min) are much higher as compared to MRR at initial setting level which paves the way towards higher production rate. It may be noted that there is a good agreement between the predicted grey relational grade (0.8351) and experimental grey relational grade (0.8552) and therefore the condition **ME2-N3-**

F3-d3 of the process parameters combination was tested as optimal. This encourages applying grey relational analysis for optimizing multi response problems.

- Further, Analysis of variance (ANOVA) depicts that machining environment signifies the most followed by the depth of cut affecting multi response characteristics with machining environment 35.93%, depth of cut 27.11%, spindle speed 4.55% and feed 2.69, respectively.

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